Self-guiding Backscattering Immune Transportation of Light in the Visible Range

Qiuyue Zhang 1, Xun Li 1,2,3, Senior Member, IEEE

1Wuhan National Laboratory for Optoelectronics, Huazhong University of Science and Technology, Wuhan 430074, China
2Department of Electrical and Computer Engineering, McMaster University, Hamilton, ON L8S 4K2, Canada
3School of Information Science and Engineering, Shandong University, Qingdao, 266237, China

Corresponding author: Xun Li (e-mail: lixun@mcmaster.ca).

Abstract: The implementation of topological photonic systems at optical frequency is of great significance for practical applications. In this work, we extend the study of unidirectional transmission to the visible light range with a relatively simple structure. We theoretically demonstrated the existence of self-guiding one-way edge modes at the interface between air and a hexagonal lattice of rods with a layered plasmo-semiconductor-gyroelectric metamaterial as the background medium. The inherent loss in metals can be compensated by the incorporation of the semiconductor layers with optical gain. Our simulation result shows that the self-guiding transmission remains 82% over a distance of about 30 wavelengths. In addition, it renders the light travel on such an interface insensitive to obstacles or impurities either on-purposely introduced or caused by manufacturing imperfections or variations. We show that the power transmission remains around 80% even in the presence of deliberately introduced obstacles. By exploiting the robust self-guiding unidirectional transport feature, we have designed a shape-independent cavity that can tolerate sharp corners in different angles, which eliminates the reflection and relaxes the geometrical constraint in design of integrated photonic devices.

Index Terms: layered plasmo-semiconductor-gyroelectric metamaterial, backscattering immune and self-guiding transportation

1. Introduction

Numerous theoretical [1-9] and experimental [10-16] investigations based on the photonic topological insulators (PTIs) have been widely reported due to their unique feature of backscattering-immune transmission regardless of the presence of disorders or defects. The extraordinary unidirectional characteristics make it possible to remove the requirement of isolators [17, 18]. Furthermore, the robustness insures the immunity of the optical devices to performance degradation induced by impurities or fabrication imperfections [19-25]. However, on account of the generally very weak magnetic response and fabrication difficulty at optical frequency, most topological photonic designs are limited to microwave frequencies, and the device size is too large to be integrated on chip [26]. The implementation of topological photonic structures at optical frequency is of great significance for practical applications. Although some designs operated at optical frequency have been reported, major technique hurdles still exist in fabricating the proposed artificial metamaterials that possess complicated geometric structure with eminently precise parameters [2, 15, 16]. Exploiting a relatively simple structure to achieve a similar functionality at optical frequency may provide new opportunities to prompt the development and applications of PTIs.

The brokenness of the time-reversal symmetry (TRS), as generally required in constructing PTIs, can be realized even at visible frequencies by using gyroelectric materials [27, 28]. However, Wang et al. [1] pointed out that the Voigt parameter of conventional gyroelectric materials is very small (in the order of
~10^{-3}$), resulting in weak TRS breaking strength and the inability to form an observable topological bandgap. The Voigt parameter (characterized by the ratio of the off-diagonal element to the on-diagonal element of the permittivity tensor) represent the TRS breaking strength. Increasing the value of the Voigt parameter may provide a way to implement PTIs at visible frequencies. Very recently, Wu et al. [9] studied one-way edge modes in the visible frequencies based on a layered plasmo-gyroelectric structure. By reducing the strength of the on-diagonal elements of the permittivity tensor to increase the Voigt parameter, they managed to raise the bandgap by orders of magnitude. In addition, their approach does not require any complicated geometrical structure. However, since the edge modes is located in the light cone, a metal wall has to be attached to the interface of the arrays to prevent light from scattering into the free space, as otherwise the one-way transmission behavior will disappear. And the performance of the layered structure in the visible light range is significantly limited by the inherently strong loss in metallic layers [29-31].

In this work, we have studied the self-guiding unidirectional edge modes at the interface of a hexagonal photonic crystal (PC) consisting of rods in a layered plasmo-semiconductor-gyroelectric metamaterial (PSGM), with the semiconductor gain medium introduced in attempt to compensate the metal loss. The simulation result shows that the electromagnetic wave is strongly bound to the interface of the PC without the need of an auxiliary cladding layer. This work can be viewed as an extension of [11, 32] to optical frequency. In addition, we show that the self-guiding edge modes are robust to obstacles or impurities either on-purposely introduced or caused by manufacturing imperfections and variations. As an application, a geometry-independent robust cavity is proposed. Such a cavity only supports either clockwise or anticlockwise, but not both, rotating waves and the unidirectional transportation is robust against sharp corners in different angles.

We begin with a detailed description of the proposed structure and the material parameters in section 2. We then present the corresponding band diagram analysis and the unidirectional propagation characteristics in section 3. The ability of resisting defects is demonstrated in the followed section 4. As a potential application, a geometry-independent robust cavity is also proposed in this section. All simulation results in this work were obtained with the finite element method (FEM).

2. The Geometric Structure and Material Parameters

The schematic geometry of our proposed structure is depicted in Fig. 1. The background material of the two-dimensional PC consists of alternating PSGM layers having thickness filling factors $\delta_p$, $\delta_s$ and $\delta_g$ ($\delta_p + \delta_s + \delta_g = 1$), respectively. The metallic layers (consist of Silver) are described by $e_i = e_{\infty} - \omega_0^2 / (\omega^2 + i \gamma_0)$, where the macroscopic permittivity $e_{\infty} = 6$, the plasma frequency $\omega_p = 1.5 \times 10^{16}$ rad/s and the collision frequency $\gamma = 7.73 \times 10^{13}$ rad/s are obtained by fitting the available experimental data for the Silver film over the wavelength range of interest [33, 34]. InGaN (the refractive index is about $n = 2.4$ in the visible range [35]) is chosen as the gain medium and the relative permittivity $e_{\infty}^{g}$ (the gain in the semiconductor can be modeled by adding a negative imaginary part $\varepsilon_{\text{rad}}$ to the dielectric constant). The material gain is given by the standard relation $g_0 = -\varepsilon_{\text{rad}}^g / (nc)$. We set the material gain as $g_0 = 1.5 \times 10^4$ cm$^{-1}$ in this work, which is sufficient to compensate the loss in metallic layers. The material gain as high as $1.5 \times 10^4$ cm$^{-1}$ can be easily obtained with a 450 nm optically pumped nitride-based laser [36-38]. In the presence of an externally applied magnetic field along the z-axis, the relative permittivity of the gyroelectric layers (consist of Bi-substituted Yttrium Iron Garnet) in the visible range is described by the dielectric tensor $\varepsilon_g = [\varepsilon_{22}, i\varepsilon_{13}, 0; -i\varepsilon_{13}, \varepsilon_{33}, 0; 0,0,0]$, where $\varepsilon_{22} = 5.5 + 0.0025 i$ and $\varepsilon_{33} = (1 + 0.01) \times 10^{-2}$ [39]. Note that in the absence of an externally applied magnetic field $\varepsilon_{22} = 0$. According to the effective medium theory, the relative effective permittivity of the layered PSGM is taking the form of $\varepsilon_{\text{eff}} = [\varepsilon_{xx}, i\varepsilon_{xy}, 0; -i\varepsilon_{xy}, \varepsilon_{zz}, 0; 0,0,0]$, the expressions of these tensor components are given
To obtain an appropriate value of the Voigt parameter, we perform a series of numerical simulations for different $\delta_p$, $\delta_s$, and $\delta_g$. By setting the thickness filling factors as $\delta_p = 0.455217$, $\delta_s = 0.418889$, and $\delta_g = 0.125894$, at the wavelength of 450 nm, the relative effective permittivity tensor of the background material is 

$\hat{\varepsilon}_{eff} = \alpha \left[ 2, i(2.4 + 0.024i), 0; -i(2.4 + 0.024i), 2, 0; 0, 0, 66143 - 2126i \right]$, here $\alpha = 5.245579 \times 10^{-4}$ denotes the frequency renormalization scaling factor. Notably, the simulation results are independent of the value of $\varepsilon_{zz}$. The corresponding Voigt parameter $V = |\varepsilon_{yy}| / |\varepsilon_{xx}|$ is 1.2, much larger as compared to that in the conventional gyroelectric material (equal to 0.0018). The high Voigt parameter in the PSGM is obtained by suppressing the on-diagonal permittivity tensor components via the plasmonic (negative) response of the metallic layers. The hexagonal lattice of rods immersed in the PSGM are composed of stacked plasmo-semiconductor-dielectric metamaterial (PSDM) layers. All relevant parameters in the metallic and semiconductor layers remain the same as in the layered PSGM. Therefore, the thickness filling factor of the dielectric layers (consist of TiO$_2$ with relative permittivity $\varepsilon_i = 5.6 + 0.0024i$) is $\delta_d = \delta_g = 0.125894$. The relative effective permittivity of the PSDM rod is $\varepsilon_d = \alpha \cdot \text{diag} \{26 - 0.024i, 26 - 0.024i, 67093 - 2189i\}$ and the rod radius is $r = 0.37a$ ($a$ is the lattice constant). To the best of our knowledge, the layered metal-dielectric structures have been experimentally realized across the optical spectrum [42, 43]. Hence, our proposed layered structure is experimentally feasible based on the current nanofabrication technologies. Note that in the absence of pumping in the nitrides, the Voigt parameter of PSGM layers is in the order of $10^{-3}$, resulting in the inability to form an observable topological bandgap and the disappearance of the unidirectional transmission. Thus, the on/off states of the light transmission can be controlled by the optical pumping.

Fig. 1. (a) A hexagonal lattice PC of PSDM rods in the PSGM background. The stacking direction is along the $z$-axis. The semiconductor layer is pumped to achieve optical gain. (b) Enlarged view of the unite cells of the hexagonal two-dimensional PC. $\varepsilon_d$ and $\varepsilon_{eff}$ are the effective relative permittivity of the rods and the background material, respectively.

3. Self-guiding Unidirectional Transmission

The band diagrams of a two-dimensional hexagonal lattice of PSDM rods in the PSGM for transverse electric polarization are shown in Figs. 2(a) and 2(b). The results are obtained by performing a finite element Eigenfrequency scheme and imposing period boundary conditions (PBCs) at the primitive cell's borders. In the absence of an externally applied magnetic field, as depicted in Fig. 2(a), the second and third bulk bands cross at point $K$ (pointed by a red arrow) of the Brillouin zone. While in the presence of an external magnetic field applied in the $z$ direction, the bands forming the degenerate point in Fig. 2(a)
split apart and a complete bandgap of about 24% relative size (twice as large as the bandgap in [9]) is obtained as highlighted in yellow in Fig. 2(b). By using FEM Eigenfrequency calculations and applying PBCs at the supercell’s (including 10×1 primitive cells of the PC) borders, we obtain the corresponding projected band diagram. As shown in Fig. 3(a), the red and blue curves are the edge modes in the bandgap, which have only negative or positive group velocities (the slope of the dispersion curves are equal to group velocities \( v_g = \frac{d\omega}{dk} \)), indicating the unidirectionality of the edge modes. It is noteworthy that the edge modes are outside the light cone (shadowed grey area in Fig. 3(a)) and are evanescent in the free space. Hence the electromagnetic waves can be guided at the interface of the PC without using an ancillary cladding (generally a metal wall or a PC with overlapped bandgap) as shown in Figs. 3(b) and 3(c). This feature is completely different from the design described in [9], as the latter requires an a metal wall to prevent light from leaking into the free space. As shown in Fig. 3(e), without the metal wall, electromagnetic waves cannot be confined to the interface of the PC but leak into the free space completely. This happens because the corresponding edge modes are inside the light cone and thus be leaky, while this will never happen in our proposed structure. In addition, the transmission direction can be reversed by flipping the sign of the externally applied magnetic field as demonstrated in Figs. 3(b) and 3(c).
externally applied magnetic field. Perfectly matched layers are applied to the boundaries to prevent the waves from interfering with themselves. (d) The amplitude of magnetic field distribution of the unidirectional waveguide at $0.65(2\pi c/a_x)$ in [9]. The yellow line indicates the metal wall, which is used to prevent the electromagnetic waves from leaking into the free space. (e) When the metal wall is removed, the electromagnetic waves leak into the free space and the one-way transmission behavior disappears. Point sources (white stars) are placed at the interface as the radiation sources. Colorbar represents the magnetic field strength.

4. Robustness of the Edge Modes and the Geometry-independent Cavity

In this section, four different types of interfacial obstacles are on-purpose introduced to demonstrate the robustness of the edge modes. The case where no obstacles are introduced is also presented (Fig. 4(a)) and the corresponding power transmission remains 82% over a distance of about 30 wavelengths, as shown in Fig. 4(f). The energy loss is mainly due to the gyroelectric layers that we exploited in this structure. In all five cases, point sources (schematically marked by white stars) placed at $(47.5a_y,0)$ are used to excite the surface waves and operate at $0.26(2\pi c/a_x)$.

Fig. 4(b) shows the first type of interfacial obstacle, including the replacement of a PSDM rod placed at $(24a_y,0)$ with a Copper rod of the same size. A new interface is formed between the edge of the Copper rod and the PSGM, allowing the electromagnetic waves to travel along the interface and keep going forwards. The second type of interfacial obstacle is created by removing a PSDM rod placed at $(24a_y,0)$ and leaving with an air hole, thus forming a small bend at the interface. Since there are no backward-moving modes at the same frequencies, the left-moving is still unaffected as shown in Fig. 4(c). The third type of obstacle shown in Fig. 4(d) is a rectangular vacuum cavity. It is found that the left-moving electromagnetic wave transmits seamlessly around the sharp corners without introducing backscattering. Furthermore, we demonstrate that this behavior is universal and is independent of the size and shape of the cavity. The forth type of interfacial obstacle is an inserted metal plate (size $0.2a_x \times 0.3a_y$) at $x = 24a_x$ as shown in Fig. 4(e). This case is similar to the case in Fig. 4(b), except for the sharp corners of the former one. The inserted metal plate creates a new path for electromagnetic waves to bypass the sharp corners without being reflected. However, for a conventional interface, any of these obstacles can result in strong backscattering and even hinder the transmission of the light. The normalized transmission spectra as a function of $x/a_x$ for the five cases is illustrated in Fig. 4(f). It is found that these obstacles have little effect on the self-guiding unidirectional transmission, and only a few percent of energy inevitably leaks into the free space. The self-guiding transmission remains around 80% regardless of the existence of the four types of deliberately introduced obstacles, as shown in Fig. 4(f). The results in the current work are not substantially affected by the material dispersion [1, 27, 44].
Fig. 4. Under an externally applied magnetic field along +z direction, the amplitude of the magnetic field distributions at the interface between air and the PC (a) in the absence of obstacles, (b-e) in the presence of four different types of interfacial obstacles including: (b) replacing a PSDM rod at \((24a,0)\) with a copper rod of the same size, (c) taking away a PSDM rod at \((24a,0)\) and leaving with an air hole, (d) a rectangular vacuum cavity, (e) inserting a metal plate (size \(0.2a \times 0.3a\)) into the interface at \(x = 24a\). In all five cases, the point sources (white star) placed at \((47.5a,0)\) operate at \(\pi 0.26 2ca\). Colorbar represents the magnetic field strength. (f) The normalized transmission spectra as a function of \(x/a\) for (a)-(e).

Resonant cavity is a critical component of the laser, while its geometrical constraint and unwanted back-reflection hinder the optical integration. Based on the self-guiding robust feature of the edge modes, we propose a deformed robust cavity which relaxes the geometrical constraint and eliminates the reflection as shown in Fig. 5(a). A point dipole placed near the PC is used to excite the cavity mode. The Poynting vectors distributions corresponding to part I, part II and part III in Fig. 5(a) are shown in Figs. 5(b)-5(d), respectively. It is found that even in the presence of sharp corners in different angles, the power flow circulates clockwise along the interface of the deformed cavity without introducing backscattering. In addition, when the externally applied magnetic field is flipped, the flow direction would switch to the anticlockwise direction accordingly, which may offer flexible ways for light manipulation. The investigation
of geometry-independent robust cavity may offer an opportunity to design complex integrated photonic circuit which is not restricted by the geometry and reciprocity.

Fig. 5. (a) The amplitude of magnetic field distribution in the deformed cavity. The point source (marked by a white star) operates at $0.2668 \times \left(\frac{2\pi}{a}\right)^2$ (near the resonant frequency of the cavity). (b-d) The Poynting vectors distributions correspond to part I, part II and part III in (a). The power flow circulates clockwise along the interface of the cavity without introducing backscattering. Colorbar represents the magnetic field strength.

5. Conclusions
In conclusion, the self-guiding unidirectional transmission at the interface between air and the PC consisting of PSDM rods in a layered PSGM has been numerically investigated in the visible light range. The Voigt parameter of the layered PSGM is 1.2, much higher as compared to that in the conventional gyroelectric material (in the order of $10^{-3}$). As a result, a wide and robust bandgap of about 24% relative size is obtained. Since the edge modes lie outside the light cone, the electromagnetic wave travels along the interface of the PC without the need of an ancillary cladding and the transmission direction depends on the orientation of an externally applied magnetic field. In addition, due to the absence of the backward propagating modes at the same frequencies, the backscattering is completely suppressed, which makes the unidirectional transportation unaffected by obstacles or impurities. We have also shown that our proposed cavity in arbitrary geometrical shape can tolerate bending in different angles, which may provide a platform for complex integrated photonic circuitry with little restrictions on geometrical shapes and reflections.

References


